Effects of Water Deficits on Yield, Yield Components, and Water Use Efficiency of Irrigated Corn

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ABSTRACT

Irrigated corn (*Zea mays* L.) is an important feed grain crop on the Southern High Plains where the supply of water for irrigation is declining. Limited irrigation—applying less water than is required to meet potential evapotranspiration—is extensively practiced on the drought tolerant crops of grain sorghum [*Sorghum bicolor* (L.) Moench], wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.). The purpose of this paper is (i) to report the effects of timing and duration of water deficit periods on growth and yield components of corn, (ii) to evaluate the seasonal evapotranspiration requirements of corn, and (iii) to give further information regarding the adaptation of corn for limited irrigation in a region of normally high evaporative demand climate. In a 4-yr study, corn was grown under five irrigation treatments: adequate water, 2- and 4-week water deficit periods during vegetative growth, and 2- and 4-week water deficit periods during grain filling. Water deficits imposed 41 days after planting reduced leaf, stalk, and ear yields, while those imposed 55 days after planting reduced only stalk and ear yields. Deficits during vegetative growth reduced kernel numbers but had little effect on weight per kernel. Deficits during grain filling did not affect leaf and stalk yields but reduced ear yields. Kernel numbers were not affected by water deficits during grain filling unless severe deficits were imposed early in the period; thus, grain yield reductions were proportional to reductions in weight per kernel. With adequate water, seasonal water use averaged 964 mm on graded furrows and 834 mm in level borders. Although water use efficiency (WUE) was sometimes increased slightly when plants were subjected to water deficits, the data indicate that limited irrigation of corn would not be feasible on the Southern High Plains.

Additional index words: Water use, Limited irrigation, Weight per kernel, Kernel number, *Zea mays* (L.).

IRRIGATED corn (*Zea mays* L.) is an important feed grain crop on the High Plains of Texas, Oklahoma, and New Mexico. From 1966 to 1976, the area of irrigated corn in the region increased from approximately 25 000 to over 500 000 hectares, and by 1979, corn had replaced grain sorghum [*Sorghum bicolor* (L.) Moench] as the leading irrigated feed grain crop. However, after the hot, dry summer of 1980, corn production declined and in 1982, only about 225 000 hectares were planted to irrigated corn.

Groundwater depletion from the Ogallala Aquifer and increasing pumping energy costs emphasize the need for conservation and efficient use of water. Grain sorghum, wheat (*Triticum aestivum* L.), and cotton (*Gossypium hirsutum* L.) are extensively grown under limited irrigation where less water is applied than required for potential evapotranspiration (ET) and maximum yield. Reduced water application permits continued irrigation of most of the cropland in existing systems. With drought tolerant crops and significant seasonal rainfall, water use efficiency is often increased with limited irrigation (13,15). The effects of water deficits on yield, yield components, and water use efficiency of corn have not been studied extensively under the stressful conditions in this semiarid area.

Frey (5) proposed that the most critical period for yield determination in the life cycle of corn begins approximately 2 weeks before silking and continues until 2 to 3 weeks after silking. Major stress before silking may cause ears to fail to develop, while stress

after pollination results in limitation of kernel numbers or kernel abortion (19). Final kernel number is established about 2 to 3 weeks after pollination (5,9,19). Shaw (14) emphasized that the most crucial period for drought stress extends from 5 days before to 5 days after silking followed by a 30-day period that is less crucial and relatively constant in sensitivity to stress. In most studies reporting effects of drought stress on yield components, stress was induced during or after pollination. In general, maximum reductions in kernel numbers resulted from stress in the silking and early grain fill stages (3,7,10,12). Stress after 2 to 3 weeks after pollination reduced mass per kernel but did not affect number of kernels per plant.

Available information relating drought stress during vegetative growth to yield and yield components indicates that stress during that stage is less crucial than during pollination or grain filling (3,11,20). Wilson (20) found that 8 days of stress terminated 21 days before normal silk emergence reduced kernel number 20% and increased mass per kernel 7.5%.

At Bushland, TX, Musick and Dusek (11) evaluated corn yield response to water and developed functional relationships between yield and seasonal evapotranspiration (ET). They compared their results with those from other studies reported in the literature (8,12,16,17) and found that seasonal ET and yield reductions from drought stress were greater at Bushland, TX, than at other reported locations. They concluded that limited irrigation of corn involved unacceptably high risks and should not be practiced in the high evaporative demand climate of the Southern High Plains. In their work, Musick and Dusek (11) evaluted corn grain yield response to water but they did not study the effects of water deficits on vegetative growth or yield components.

The purpose of this paper is (i) to report the effects of timing and duration of water deficit periods on growth and yield components of corn, (ii) to evaluate the seasonal evapotranspiration requirements of irrigated corn, and (iii) to give additional information regarding the adaptation of corn for limited irrigation in a region of normally high evaporative demand climate.

MATERIALS AND METHODS

The studies were conducted on Pullman clay loam (fine, mixed, thermic Torretic Paleustolls) (18) at the USDA Conservation and Production Research Laboratory, Bushland, TX. The moderately permeable surface soil (0 to 0.20 m) is underlain by a dense, very slowly permeable montmorillonitic clay horizon (B22t) extending from the 0.20- through the 0.50- to 0.60-m depth. Below this depth, the soil is somewhat

more permeable. Depth to the highly calcareous *caliche* layer ranges from 1.20 to 1.50 m. At 0.03 and 1.5 MPa matric potentials, the soil contains approximately 0.43 and 0.27 m of water, respectively, in the top 1.20 m of the profile.

Experimental procedures were described in detail in a previous paper (4). Only items pertinent to this study will be given here. One of three experiments was conducted under graded furrow irrigation on an area with about 1% slope. The others were conducted in level borders. All experiments contained both fertilizer and irrigation variables but only the irrigation variables will be discussed here. Data given will be that from plots that received adequate fertilizer (210 kg N/ha as NH_4NO_3 broadcast before planting).

Irrigation dates are presented in Table 1. Irrigations were spaced to allow the crop to be fully irrigated (I-1) or subjected to water deficits 2 weeks during late vegetative growth (I-2), 2 weeks during early vegetative growth (I-2a), 4 weeks during vegetative growth (I-3), 4 weeks during grain filling (I-4), or 2 weeks during grain filling (I-5). We did not include a water deficit treatment during pollination because it is well established that corn is most vulnerable to stress during that period.

The 3-yr experiment on graded furrows consisted of five irrigation treatments and eight fertilizer treatments in a randomized block-split plot design with four replications (4). Irrigation treatments occupied main plots (9.1 by 94.1 m) and fertilizer treatments occupied subplots (4.5 by 22.9 m). Main plots contained 12 rows of corn 0.76 m apart.

Following fertilizer application each year, the site was uniformly preplant-irrigated. At both preplant and seasonal irrigations, water was applied through gated pipe and measured to individual 0.76-m spaced furrows with the bucket and stopwatch technique. In 1976, the application rate was 38 L min⁻¹ furrow⁻¹ and, in 1977 and 1978, it was 23 L min⁻¹ furrow⁻¹. Tailwater runoff of 3- to 6-h duration was measured from five furrows per plot through 0.3-m calibrated H-flumes equipped with water stage recorders. Water infiltration was determined as the difference between application and runoff.

Studies were conducted in level border plots in 1978 and 1979. Irrigation treatments were similar to those studied for graded furrows. Water was applied through gated pipe and metered to individual plots. Like the graded furrow experiment, these studies had randomized block-split plot designs with four replications. Irrigation treatments occupied main plots, and fertilizer treatments occupied subplots. In 1978, main plots were 12.2 by 46 m, and in 1979 they were 12.2 by 61 m. Subplots were 6.1 by 15.2 m both years. Main plots contained 16 rows of corn 0.76 m apart. Plots were maintained in beds and furrows for uniform water distribution.

Planting was on 28 Apr. 1976, 6 May 1977, 1 May (graded furrows) and 12 May (level borders) 1978, and 10 May 1979. Pioneer brand hybrids grown were '3369A' in 1976 and '3184' in all other years. Plant populations averaged 8.6 plants/m² in 1976, and 6.0 plants/m² in other years. Seasonal water use was determined from a water balance using beginning- and end-of-season soil water sampled to 1.8 m and seasonal irrigation and rainfall. A monthly summary of seasonal climatic data is presented in Table 2. Seasonal rainfall and nearby weather station air temperatures are published elsewhere (4). Surface water runoff was considered in water use determinations, but we did not assess profile drainage. We consider it to be minor or negligible on this soil and under the conditions of these experiments. Frequent furrow irrigation of a Pullman clay loam (1.2% slope) over a 20-yr period resulted in a depth of wetting of less than 2.5 m and estimated water percolation (below 1.8 m) of 60 mm (1). However, basin irrigation over a 20-yr period resulted in a depth of wetting of 15.5 m with estimated deep percolation of 1.5 m.

Plant samples were taken approximately weekly from about

Table 1. Irrigation treatments and dates, seasonal irrigation water applied, and seasonal water use.

Treatment	Vegetative		Polli-nation	Grain filling			Irriga-tion	Water use
							— mm —	
1976	6/14	6/28	7/12	7/28	8/11	8/27		
I-1	x	x	x	x	x	x	685	937
I-2	x		x	x	x	x	567	845
I-2a		x	x	x	x	x	582	846
I-4	x	x	x				332	641
I-5	x	x	x	x			451	757
1977	6/16	7/5	7/19	8/4				
I-1	x	x	x	x			659	984
I-2	x		x	x			481	805
I-3			x	x			341	682
I-4	x	x	x	x			659	994
I-5	x	x	x	x			659	1003
1978	6/29	7/13	7/25	8/8	8/23	9/5		
I-1	x	x	x	x	x	x	717	970
I-2	x		x	x	x	x	576	850
I-2a		x	x	x	x	x	579	845
I-4	x	x	x	x			505	781
I-5	x	x	x	x	x		634	905
1978-LB†	6/30	7/12	7/26	8/15	8/28	9/11		
I-1	x	x	x	x	x	x	635	884
I-2	x		x	x	x	x	533	772
I-3			x	x	x	x	406	648
I-4	x	x	x	x			432	676
I-5	x	x	x	x	x		533	789
1979	6/28	7/13	7/26	8/15		9/4		
I-1	x	x	x	x		x	500	783
I-2	x		x	x		x	400	693
I-3			x	x		x	300	572
I-4	x	x	x				300	631
I-5	x	x	x	x			400	710

† Level bordered site.

Table 2. Summary of May–September climatic data for 1976–1979 at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX.

	May	June	July	August	September
Precipitation, mm					
1976	38	22	31	64	67
1977	65	46	10	198	10
1978	163	77	29	44	158
1978-LB†	163	92	27	40	163
1979	6	81	44	80	10
44-yr avg	69	75	66	71	45
Evaporation, mm					
1976	181	249	224	238	149
1977	152	244	296	163	185
1978	166	174	247	228	156
1979	155	168	223	178	177
43-yr avg	201	232	247	222	179
Temperature (Max.-Min.), °C					
1976	22.8-7.4	30.7-13.4	30.1-16.3	31.6-15.4	26.2-12.2
1977	26.1-11.6	33.3-16.1	33.7-18.0	30.8-17.8	28.3-13.3
1978	24.1-9.7	29.7-16.4	34.3-18.2	30.8-15.7	26.9-12.8
1979	24.1-8.7	30.1-13.6	32.8-17.1	28.9-14.7	29.2-11.2
44-yr avg	26.2-9.6	31.1-14.9	32.6-17.4	31.7-16.4	28.2-12.3
Solar radiation, MJ m⁻² day⁻¹					
1976	23.9	27.0	24.9	23.8	18.0
1977	22.5	25.7	26.0	20.9	19.3
1978	21.9	25.4	25.8	22.9	17.3
1979	20.8	24.9	24.0	22.6	20.0
10-yr avg	24.5	26.7	24.9	23.0	18.4

† Level bordered site.

45 days after planting until physiological maturity. The I-1 treatments were sampled over the entire period, and other treatments were sampled from the initiation of treatments (skipped irrigation) until termination of treatments (irrigation) or physiological maturity. Plants were harvested from 0.76 m² areas (1-m row) of each plot. Samples were separated into leaves, stalks, and ears then oven-dried to constant weight at 60°C. Samples for grain yield determination were obtained from one 14 m² area of each plot, shelled, and adjusted to 16% grain moisture. Five-hundred grain samples for weight-per-kernel determinations were oven-dried at 60°C, counted with an electronic seed counter, and weighed. Kernels per square meter were determined from grain yield and kernel weight data.

RESULTS AND DISCUSSION

Water Deficit Effects on Grain Yields. Grain yields for irrigation treatments are presented in Table 3. Treatments that imposed 2- and 4-week water deficit periods during vegetative growth [I-2 and I-3 in 1977, 1978 (level borders), and 1979] reduced yield of corn by 23 and 46%, respectively. Delaying irrigation for 2 weeks during early vegetative growth had about the same effect on grain yield as an equivalent delay during late vegetative growth. Treatments involving water deficits during grain filling were designed to impose deficits during the final 2 and 4 weeks of that period. However, stress periods during grain filling were more variable in length than those during vegetative growth because of previous seasonal irrigation and precipitation. Thus, to measure the effects of stress during grain filling on yield, we related days before normal maturity during which water deficits were imposed to percent yield reduction (4). The relationship indicated that yields were reduced 1.2% for each day stress was imposed before normal maturity.

Water Deficit Effects on Dry Matter Accumulation. Dry matter accumulation in leaves, stalks, and ears for Treatments I-1, I-2, and I-3 in 1977 are shown in Fig. 1. In 1977, the I-2 and I-3 treatments were sampled from stress imposition until physiological maturity. The 4-week water deficit period (I-3) beginning 41 days after planting reduced dry matter accumulation in leaves, stalks, and ears throughout the remainder of the season. The 2-week deficit period (I-2) beginning 2 weeks later (55 days after planting) did not affect dry matter accumulation in leaves but reduced stalk growth during a period extending from imposition until about 100 days after planting when the ears were developing rapidly. Neither leaves nor stalks were fully developed when I-3 was imposed (41 days after planting); thus, growth of both was reduced by the water deficit. But when I-2 was imposed 14 days later, leaves were fully developed and stalks were not, so only stalk growth was reduced. Comparison of I-2 and I-3 with I-1 indicate that treatments which experienced deficits during stalk growth translocated less dry matter later to filling grain than the fully irrigated treatment. Ear yields for I-2 and I-3 were 90 and 64% of the control, respectively, in 1977. Dry matter accumulation curves from data collected from 47 to 96 days after planting in 1979 are similar to those for a like period in 1977 (data not shown).

Dry matter accumulation in ears for Treatments I-1, I-4, and I-5 in 1976 are shown in Fig. 2. Accumu-

Table 3. Grain yields as affected by water deficit treatments.

	1976	1977	1978	1978-LB†	1979†	Avg.	% of I-1
			Mg/ha				
I-1	9.13a*	8.27a	8.29a	8.66a	11.22a	9.11	100
I-2	8.39a	5.18b	7.57ab	6.24b	10.20ab	7.52	83
I-2a	8.36a		6.66b			7.51	86‡
I-3		3.47c		2.53c	9.26bc	5.09	54‡
I-4	4.40c	7.99a	7.59ab	7.82ab	8.85c	7.33	80
I-5	6.45b	8.04a	8.06a	8.83a	10.47a	8.37	92

* Within columns, means followed by the same letter are not significantly different (5% level).

† Experiment designated 1978-LB and that conducted in 1979 were in level borders; others were on graded furrows.

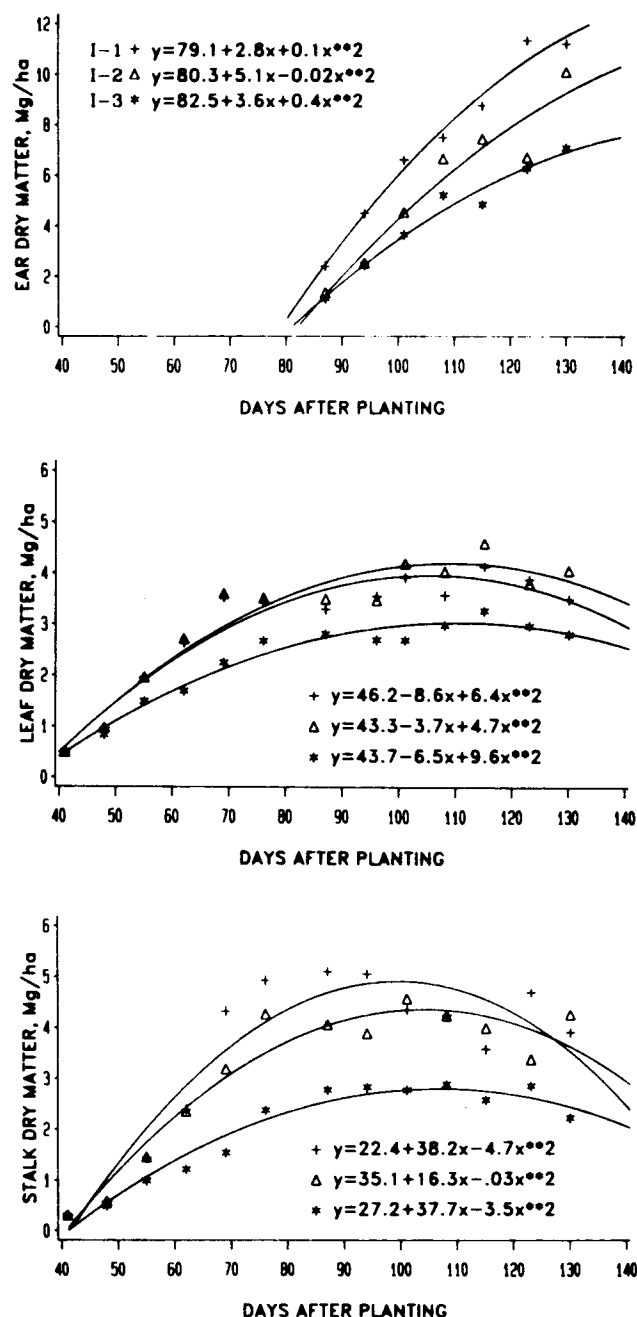‡ Percent of I-1 considering only years in which the treatment was studied.

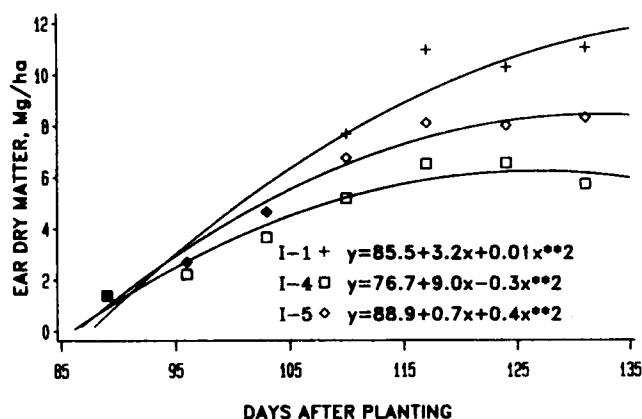Fig. 1. Dry matter accumulation in ears, leaves, and stalks, treatments I-1, I-2, and I-3, 1977.

Fig. 2. Dry matter accumulation in ears, treatments I-1, I-4, and I-5, 1976.

lation in leaves and stalks was similar for the three treatments; thus, those curves are not shown. When water deficits occurred, dry matter accumulation in ears slowed and as deficits were prolonged, plants dessicated and dry matter accumulation ceased. Deficits imposed for the last 20 and 34 days of the grain filling period reduced ear yields about 24 and 47%, respectively. Data for 1978 and 1979 gave curves similar to those for 1976; however, yield reductions were not as severe as those in 1976 (data not shown).

Water Deficit Effects on Yield Components. Weight per kernel and kernels per square meter are given in Tables 4 and 5, respectively. Weight per kernel was not measured in 1979. The data show that water deficits during vegetative stages had comparatively little effect on weight per kernel. In 1976, a 2-week water deficit period late in the vegetative stage increased weight per kernel 23%, and in 1978, a similar period early in the vegetative stage decreased weight per ker-

Table 4. Weight per kernel as affected by water deficit treatments.

Treatment	1976	1977	1978	1978-LB†	Avg	% of I-1
			mg			
I-1	222b	223ab	290a	301ab	259	100
I-2	273a	240a	299a	311a	281	108
I-2a	251ab		262b		257	100‡
I-3		209b		291bc	250	95‡
I-4	152c	221ab	243b	268c	221	85
I-5	166c	230ab	261b	293ab	238	92

* Within columns, means followed by the same letter not significantly different (5% level).
† Experiment designated 1978-LB in level borders; others were on graded furrows.
‡ Percent of I-1 considering only years in which the treatment was studied.

Table 5. Kernel numbers as affected by water deficit treatments.

Treatment	1976	1977	1978	1978-LB†	Avg	% of I-1
			kernels/m²			
I-1	3366a*	3101a	2399ab	2405a	2818	100
I-2	2578b	2226b	2130b	1686b	2155	76
I-2a	2779b		2131b		2455	85‡
I-3		1373c		730c	1051	38‡
I-4	2475b	3035a	2625a	2455a	2648	94
I-5	3264a	2921a	2588a	2540a	2828	100

* Within columns, means followed by the same letter are not significantly different (5% level).
† Experiment designated 1978-LB in level borders; others were on graded furrows.
‡ Percent of I-1 considering only years in which the treatment was studied.

nel 10%. There were trends toward decreased weight per kernel from 4-week deficit periods in the vegetative stage, but differences were not significant at the 5% level of probability. Deficits during grain filling reduced weight per kernel in all seasons during which the treatments were imposed. No deficit occurred during grain filling in 1977. Reductions in weight per kernel tended to be proportional to the lengths of deficit periods. Excluding 1977, average reductions in weight per kernel for I-4 and I-5 were 18 and 11%, respectively.

Kernel numbers were reduced by water deficits during vegetative growth (Table 5). Reductions in number of kernels produced were greater from 4-week than from 2-week deficit periods. Data from 1977 and 1978 show that 2- and 4-week deficits during vegetative growth reduced kernel numbers 29 and 62%, respectively. Reductions in seed numbers as a result of water deficits late in the vegetative period (I-2) were similar to those resulting from deficits earlier in the vegetative period (I-2a). Since the potential size of the ear and the number of ovules formed are determined during the vegetative period (6), one would expect kernel numbers to be reduced by water deficits during vegetative growth.

Water deficits during grain filling did not affect kernel numbers except in 1976 when the deficit was imposed 34 days before normal physiological maturity (about 26 days after silking). Researchers generally agree that final kernel number is established about 2 to 3 weeks after pollination (5,9,19). A reduction in kernel numbers from deficits imposed after that time was measured in this study. In this case, it is possible that some kernels were still small and light when filling stopped and were lost in shelling and cleaning.

Compensation in weight per kernel occurred in some cases where kernel numbers had been reduced by water deficits during the vegetative stage. In 1976, the number of kernels per square meter on I-2 was 23% lower and weight per kernel was 23% higher than on I-1. Thus, yields on the two treatments were not significantly different. This indicates that when the number of kernels is limited in relation to leaf area, reduction in kernel numbers may be compensated by an increase in weight per kernel. However, the increase in weight per kernel may be partially due to shortening the ear and eliminating some of the smaller kernels. In 1977, the decrease in kernel number was 28% and the increase in weight per kernel was only 7%, and in 1978, kernel numbers were reduced and weight per kernel was not affected. Thus, there is no certainty that weight per kernel will be increased when kernel numbers are reduced by water deficits during vegetative growth; however, there may be a potential for increased weight per kernel when kernel numbers are reduced by deficits after major leaf area development.

Water Use-Yield Relationships. On the graded furrow study, seasonal water use on the adequately irrigated treatment was 937, 984, and 970 mm in 1976, 1977, and 1978, respectively (Table 1). In level borders, it was 884 and 783 mm in 1978 and 1979, respectively. The higher water use on graded furrows was associated with more water being applied at each irrigation than in the level border plots. The additional water was applied to obtain uniform wetting of the plot area. In studies conducted in level borders, Mu-
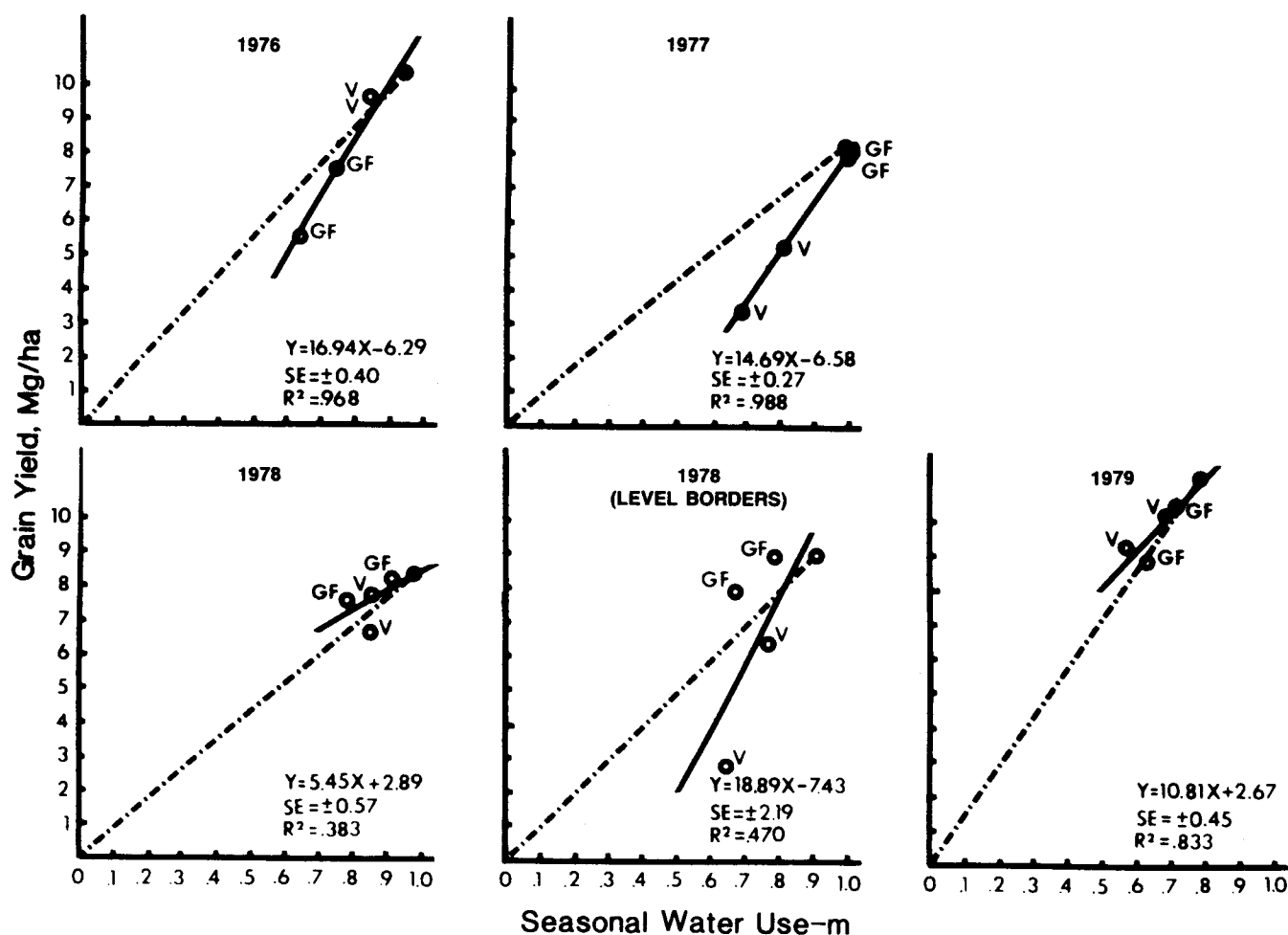
Fig. 3. Seasonal water use-grain yield relationships. V = stress during vegetative growth, GF = stress during grain filling.

sick and Dusek (11) found the seasonal ET of adequately irrigated corn in the Southern High Plains to be in the range of 750 to 800 mm. In 1979, water use in our studies in level borders fell in that range but exceeded it in 1978. The higher water use measured in this study was possibly due to higher evaporation. Musick and Dusek (11) found five seasonal irrigations to be adequate in most seasons, while in this study, six seasonal irrigations were applied in 1976 and 1978. Also, Musick and Dusek (11) applied 80 mm of water per irrigation, while 100 mm or more were applied in this study. Thus, there was more water available for evaporation in our studies. Also, even though water movement through the Pullman profile is very slow, it is possible that some water was lost to percolation below the root zone.

Grain yields were related to water use by linear regression (Fig. 3). Yields were significantly related to water use in all years except 1978. The water use efficiency (WUE) values on unstressed treatments in the graded furrow studies were 0.97, 0.84, and 0.85 kg grain/m³ in 1976, 1977, and 1978, respectively, while in the level border studies they were 0.98 and 1.43 kg grain/m³ in 1978 and 1979, respectively. Water use efficiency values reported here were lower than those of Musick and Dusek (11) except in 1979 when WUE values were similar to those of Musick and Dusek (11), and yields were higher than those obtained in their study. In Fig. 3, the dotted lines from the origins to

yields on unstressed treatments represent average WUE for the unstressed corn yields. Values falling above or below the line exhibit higher or lower WUE than the unstressed treatment, respectively. Deficits during grain filling severely reduced WUE in 1976, while those during vegetative growth caused drastic reductions in WUE in 1977 and 1978 (level border study). Even though water deficits did not decrease WUE in some instances, the grain yield-water use relationships do not show that WUE in corn grain production can be increased appreciably by withholding irrigations during vegetative or grain filling stages of growth.

In these studies, water deficits imposed during vegetative and grain filling stages had similar effects on corn grain yields. Yield reductions from 2- and 4-week deficit periods during vegetative growth were 23 and 46%. With reductions of 1.2% for each day stress was imposed, similar deficit periods during grain filling would give reductions of 17 and 33%. Considering that the data were not all obtained in the same seasons and the variations in temperature and precipitation in the different seasons, the moderately greater reductions from deficits during vegetative growth cannot be interpreted to mean that deficits during that stage are more harmful than those during grain filling. As documented in the literature (5,12,14), corn is most sensitive to water deficits during pollination.

Water deficits during early or late vegetative growth gave similar grain yield reductions. Yield potential was

reduced through reductions in leaf and stalk weights (photosynthetic area and early carbohydrate storage) and kernel numbers. Deficits during early vegetative growth reduced leaf, stalk, and ear yields, while those during late vegetative growth reduced stalk and ear yields. Compensation in weight per kernel occurred in some cases where kernel numbers were reduced, indicating that there may be a potential for increased weight per kernel when kernel numbers are reduced by deficits after major leaf area development.

Yield reductions from water deficits during grain filling were manifested in reduced weight per kernel. Logically, kernel weights were reduced due to reduced net photosynthesis, reduced translocation of dry matter from stalks to the grain, and accelerated leaf senescense.

Boyer and McPherson (2) have shown that water deficits cause drastic reductions in net photosynthesis during grain filling. They have also found that in corn, about half of the dry matter accumulated by the shoot is ultimately moved into the grain. In their studies, translocation was less sensitive than photosynthesis to water deficits.

Seasonal water use by adequately watered corn ranged from 783 to 984 mm, depending on climatic conditions and method of irrigation (graded furrows or level borders). Water deficits reduced yields and did not increase WUE; thus, these results do not indicate that limited irrigation of corn is a feasible practice on the Southern High Plains.

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